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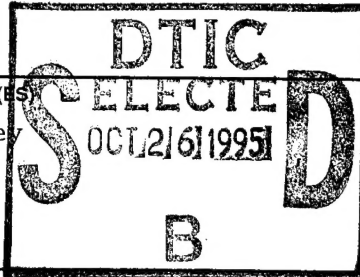
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13. ABSTRACT (Maximum 200 words)

The research involved the feasibility of multi-domain Gunn diodes. The resulting device would act as a number of ordinary diodes conducted in series as it would be a better match to the circuit with reduced losses. This leads into a significant increase in output power(at 3GHZ on the order of N<sup>2</sup>).

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Improvements in Oscillators for Planar Millimeter-Wave Circuits

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## FINAL REPORT TO ARO

S.E. Schwarz  
March 31, 1995

### 4.A. Statement of the problem studied

#### Multi-domain Gunn Diodes

It is well known that the low impedance of high-frequency Gunn diodes tends to reduce circuit efficiency. As a solution to this problem, we have studied the possibility of multi-domain Gunn diodes.[] In an N-domain diode, there would be a sequence of N domains simultaneously moving from the cathode toward the anode. The resulting device would be like a number of ordinary Gunn diodes connected in series. The impedance of the device would increase in proportion to the number N of domains acting in series, and this would result in better matching to the circuit, with reduced losses. The projected increase in output power is not small. At frequencies on the order of 30 GHz, increases in output power on the order of  $N^2$  are expected.

The multi-domain diode is much like N single-domain diodes connected in series. (However, actually connecting ordinary diodes in series is probably unfeasible, because of the parasitics of the interconnections. Instead, the diodes must be monolithically integrated.) The ac voltage across the multi-domain diode is N times as large as the ac voltage across a single-domain diode. This is because the electric field inside the diode is still equal to the critical field  $F$ , while the diode is N times longer. Let us assume that the device conductance  $G_D$  is fixed at  $G_{\max}$ , the largest value consistent with acceptable circuit efficiency. Then the power produced by the diode is approximately

$$P \approx \frac{V_{ac}^2 G_D}{2} \approx \frac{N^2 F^2 V_{sat}^2 G_{\max}}{2 f^2} \quad (10)$$

Thus we see that the limitation imposed by the power-impedance product is relaxed. Insofar as this limit is concerned, an N-domain diode can produce  $N^2$  times as much power at a given frequency as a single-domain diode. Hence multi-domain diodes will be particularly useful for increasing the low output powers obtained from Gunn diodes in the millimeter-wave range.

To our knowledge, multi-domain Gunn diodes were first proposed in a paper by Slater and Harrison in 1976.[2] They did not mention the possible improvement of circuit efficiency attendant on increasing the device impedance, perhaps because their frequency of interest was low, only 2 GHz. However, they did succeed in demonstrating two- and three-domain oscillators at that frequency. Their devices were "horizontal" (conduction parallel to the semiconductor surface), and they used a rather crude technique for nucleating the additional domains: they mechanically inscribed scratches across the diode, to create localized high-field positions. Despite the primitive nature of their devices their results were promising. They obtained 5-6 per cent overall efficiency in a 3-domain device, and interestingly, the efficiency seemed to increase with the number of domains.

Originally we carried out our own computer study of multi-domain Gunn diodes. The program being used was written here, and is a typical one-dimensional partial-differential-equation-solver such as has been used by many workers in this field. We have concentrated on new designs made possible by MBE. With this technology one can create well-controlled doping minima to act as nucleation points. However, we determined from simulations that it is also important to be able to "kill" domains; otherwise there is a tendency for some to grow large at the expense of the others.

Our plan was to fabricate multi-domain diodes by means of MBE, initially in the frequency range 30-50 GHz. We would then attempt to verify that true multi-domain operation was being attained. It was expected that improvements in available output power would be obtained.

## Boundary Conditions for Finite-Difference Analysis

The second major thrust of our effort has been an investigation of the new "Measured Equation of Invariance" (MEI) technique, especially its potential in computer-aided design of planar microwave circuits. This technique is interesting because it offers the possibility of analyzing the electromagnetic fields of oddly-shaped structures more quickly than has heretofore been possible. In essence it resembles the versatile finite-difference method, but requires a much smaller number of mesh points at which fields must be calculated, and therefore computes a great deal faster. Being new, its potential applicability is still being explored. (In fact, even the fundamental principles behind it are not yet well understood.) However it seems to work well enough to be of considerable interest. The MEI method was originally designed for free-space electromagnetic scattering problems. [3] We have applied it to calculation of the fields of microstrip discontinuities. The first goal was to calculate the fields of a microstrip step-in-width. Once this can be done (and the results agree with those already known) we can attempt to apply it to more complicated circuit elements, such as spiral inductors, for which present methods are quite inadequate. The maximum hope is that the method could be used to analyze portions of a circuit containing several circuit elements, or perhaps even the entire circuit. This seemingly ambitious goal might be realizable, because the method can, in principle, treat arbitrarily complicated shapes, while computing much faster than existing numerical methods. This would be quite an important technique, if it can be developed along the lines just described.

## 4.B. Summary of the Most Important Results

### Multi-Domain Gunn Diodes

Multi-domain Gunn diodes were fabricated in-house, in collaboration with Alpha Industries, and by outside vendors. The most successful design was a two-domain device for 15 GHz. These were tested in waveguide mounts and in coaxial structures. Efficiencies on the order of 5% were achieved.

The greatest difficulty was that of determining for sure exactly what mode of oscillation was taking place. Is it really two-domain operation, or is one of the two drift spaces simply acting as a lossy series impedance? In order to verify this point we performed increasingly careful computer simulations of the device, and simultaneously, more and more careful measurements. The latter were complicated by the need for de-embedding the device. Accurate knowledge of the package and mounting structure were required. For this purpose the coaxial mount proved most suitable.

Work on verification of two-domain operation is still proceeding at the time of this writing. The bulk of the observations and calculations support belief that two-domain operation is taking place, but results are not yet conclusive. It appears that our final device design was not perfect, in that the buffer layer between the two drift spaces is a little too short, allowing domains to punch through. This would be easily correctable if work were to continue.

After several years of work on the multi-domain device, we retain our belief that the idea is sound and can lead to large increases in device power, at frequencies above 20 GHz. If funding had not ended, we would have probably achieved these results.

## Boundary Conditions for Finite-Difference Analysis

We have found that the MEI method is a promising technique for microwave CAD. Although it resembles the method of absorbing boundary conditions, the resulting boundaries are more effective. Its great advantage is simplicity. Little human analysis is needed to set up the solution for a wide variety of problems. (By comparison, the moment method requires much hand analysis, in choosing suitable basis and testing functions, calculating their transforms, and performing singular integrations.)

We began with electrostatic problems, and found the method to be highly successful. Large improvements in computing speed, as well as reduction in computing resources were obtained. We then progressed to electrodynamics, obtaining full-wave solutions to three-dimensional problems. In all cases it was found possible to terminate the finite-difference mesh very close to the structure under analysis, resulting in rapid computation.

We have analyzed flat dipole antennas, microstrip transmission lines, and a variety of microwave discontinuities. Good results were obtained for microstrip open ends, right-angle bends, and right-angle stubs. We believe the method can be extended to more complex structures, such as spiral inductors. Eventually, because of the efficiency of the computational technique, it may be possible to analyze entire planar circuits as single electromagnetic structures.

#### **4.C. List of Publications and Technical Reports**

S.E. Schwarz, M.D. Prouty, and K.K. Mei, "Radiation from Planar Resonators." **IEEE Trans. Microwave Theory Tech.** **39**, 521-25 (March 1991).

S. S. Osofsky and S.E. Schwarz, "Design and Performance of a Non-Contacting Probe for Measurements on High-Frequency Planar Circuits." **IEEE Trans. Microwave Theory Tech.** **40**, 1701-08 (August 1992).

M. D. Prouty, R. Pous, K.K. Mei, and S.E. Schwarz, "Application of the Measured Equation of Invariance to Transmission Lines and Discontinuities." 1993 IEEE Antennas and Propagation Symposium.

M. D. Prouty, S. E. Schwarz, K. K. Mei, and R. Pous, "A New Approach to Quasi-Static Analysis, with Application to Microstrip." **Microwave and Guided Wave Letters** **3**, 302-04, September, 1993.

M.D. Prouty and S.E. Schwarz, "Hybrid Couplers in Bi-level Microstrip." **IEEE Trans. Microwave Theory Tech** **41**, 1939-44, November, 1993

M. D. Prouty, K.K. Mei, S.E. Schwarz, R. Pous, and Y. Liu, "Microstrip Antennas and Discontinuities Using the Measured Equation of Invariance." International Microwave Symposium, June 1994.

#### **4.D. List of All Participating Scientific Personnel**

Professor S.E. Schwarz, Professor K.K. Mei, Mark D. Prouty, (Ph.D. awarded 1993) Kevin Heppell, (Ph.D. expected 1995) Samuel Osofsky, (Ph.D. awarded 1992) Rafael Pous, (Ph.D. awarded 1992) Fazal Ali, Jenngang Tsay, Y. Liu, X. Chiang

#### **5. Inventions**

There are no inventions.

#### **6. Bibliography**

J. Tsay, S.E. Schwarz, S. Raman, and J.S. Smith, "Multidomain Gunn Diodes." **Microwave and Optical Technology Letters** **3**, 54-60 (February, 1990).

M. Slater and R.I. Harrison, "An Investigation of Multiple Domain Gunn Effect Oscillators." **IEEE Trans. Electron Devices** **ED-23**, 560-572 (1976).

K.K. Mei, R. Pous, Z. Chen, Y. Liu, and M.D. Prouty, "Measured Equation of Invariance: A New Concept in Field Computations." IEEE Trans. Antennas and Propagation, 42, 320-28 (March, 1994).

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